NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT 973

FLIGHT INVESTIGATION OF THE EFFECT OF VARIOUS VERTICAL-TAIL MODIFICATIONS ON THE DIRECTIONAL STABILITY AND CONTROL CHARACTERISTICS OF A PROPELLER-DRIVEN FIGHTER AIRPLANE

By HAROLD I. JOHNSON

1950

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. Yearly subscription, $3.50; foreign, $4.50; single copy price varies according to size - - - - - - - - - Price 20 cents

AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight $=mg$

g Standard acceleration of gravity $=9.80665$ m/s^2 or 32.1740 ft/sec^2

m Mass $=\frac{W}{g}$

I Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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SUMMARY

A flight investigation was made to determine the effect of various vertical-tail modifications and of some combinations of these modifications on the directional stability and control characteristics of a propeller-driven fighter airplane. Six different vertical-tail configurations were investigated to determine the lateral-directional oscillation characteristics, the sideslip characteristics, the yaw due to ailerons in rudder-fixed rolls from turns and pull-outs, the trim changes due to speed changes, and the trim changes due to power changes.

Results of the tests showed that increasing the aspect ratio of the vertical tail by 40 percent while increasing the area by only 12 percent approximately doubled the directional stability of the airplane. The pilots considered the directional characteristics of the airplane unsatisfactory with the original vertical tail but satisfactory with the enlarged vertical tail. The ventral and dorsal fins tested had little effect on the directional stability of the airplane but were effective in eliminating rudder-force reversals in high-engine-power sideslips.

INTRODUCTION

A flight investigation was made by the Flight Research Division at the Langley Aeronautical Laboratory to determine the effect of various vertical-tail modifications on the directional stability and control characteristics of a propeller-driven fighter airplane. Preliminary tests had shown that the original vertical tail provided insufficient directional stability to hold the yaw following abrupt full aileron deflection (rudder fixed) below 20° at low speeds, that rudder-force reversals occurred in sideslips at low speeds with high engine power, and that the controls-free lateral-directional oscillations were poorly damped in some flight conditions. Furthermore, it was found to be difficult to maintain constant normal acceleration in steady turns and this difficulty was attributed to inability to maintain a constant sideslip angle because of low directional stability. In order to improve the directional characteristics, the following modifications were suggested: (1) an enlarged vertical tail formed by adding a tip extension to the original vertical tail; thereby the geometric aspect ratio would be increased, (2) a small dorsal fin, and (3) a large ventral fin. This report presents data showing the effects of these separate modifications and of a combination of all the modifications on the directional stability and control characteristics of the airplane.

AIRPLANE AND VERTICAL-TAIL MODIFICATIONS

General specifications of the propeller-driven fighter airplane are given in table I and a three-view drawing of the airplane is shown as figure 1. Because of fuel consumption, the center of gravity varied during the investigation from about 26.5 to 24.5 percent mean aerodynamic chord and the gross weight varied from about 8,350 to 7,800 pounds. Calculations and limited test data for widely varying center-of-gravity locations indicated the 2-percent change in center-of-gravity position encountered in the tests would have a negligible effect on the directional characteristics of the airplane. Plan forms of the original vertical tail and the enlarged vertical tail are shown in figure 2. Dimensional characteristics of the two vertical tails are given in table II. The enlarged vertical tail involved an increase in vertical-tail height of 15¾ inches and a slight increase in area from 23.73 to 26.58 square feet; however, the geometric aspect ratio (based on vertical-tail height above the horizontal-tail center line and total vertical-tail area) was increased from 1.12 to 1.58.

The plan forms and major dimensions of the dorsal and ventral fins are shown in figure 3. The small dorsal fin (fig. 4) had a sharp edge extending approximately the first three-quarters of its length along the fuselage; from that point, the edge was gradually rounded to fair into the fin leading edge. The large ventral fin (fig. 5) had a sharp edge along its entire length. Photographs of the various airplane configurations tested, in the order of subsequent data presentation, are given as figure 6.

The relation between angular travel of the rudder and linear travel of a rudder pedal along its arc is shown in figure 7.

INSTRUMENTATION

Standard NACA recording instruments were used to measure the following quantities:

(1) Calibrated airspeed
(2) Pressure altitude
(3) Normal acceleration
(4) Aileron angle
(5) Rudder angle
(6) Rudder pedal force
(7) Sideslip angle

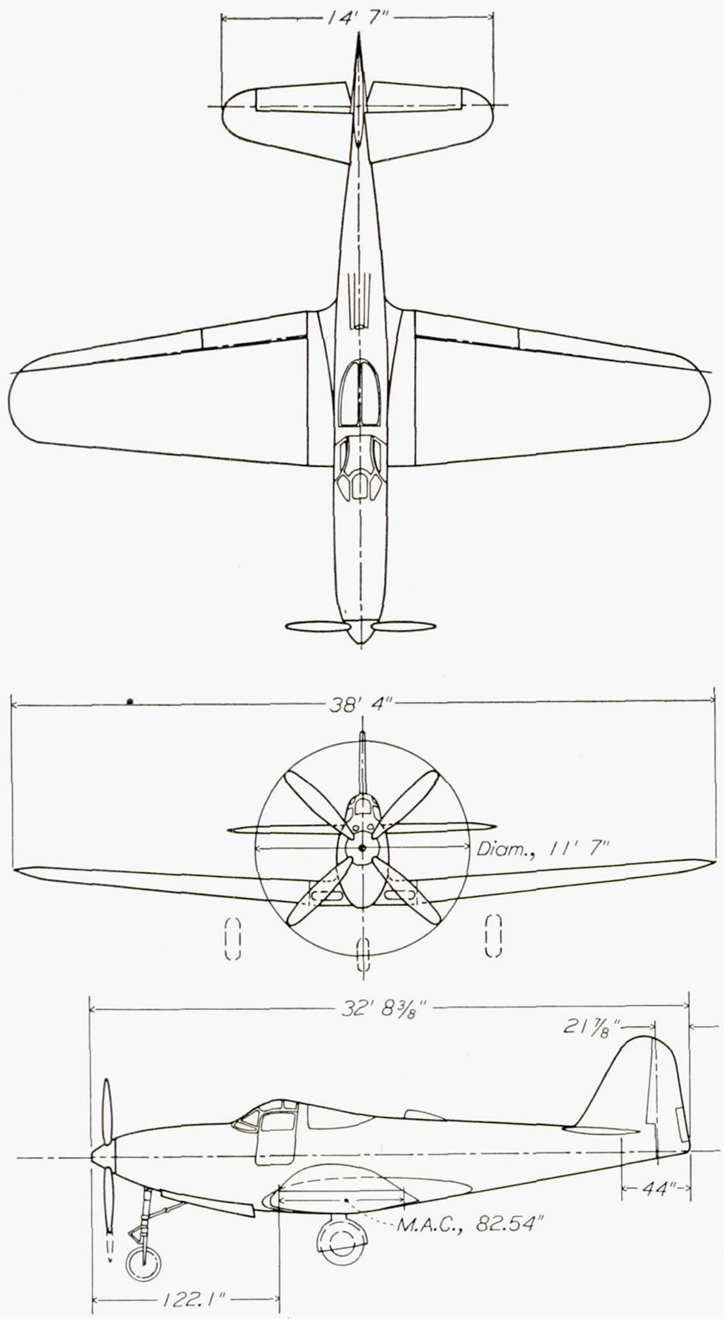


FIGURE 1.—Three-view drawing of the propeller-driven fighter airplane.

Airspeed was measured from a pitot-static tube mounted on the end of a special boom extending 1 chord length ahead of the right wing near the wing tip. Airspeed is defined by

$$V_c = 45.08 f_0 \sqrt{q_c}$$

where

V_c calibrated airspeed, miles per hour

f_0 standard sea-level compressibility correction factor

q_c difference between total pressure and free-stream static pressure (corrected for position error), inches of water

TABLE I

GENERAL SPECIFICATIONS OF PROPELLER-DRIVEN FIGHTER AIRPLANE

Engine	Allison V-1710-93
Rating:	
Take-off	1,325 bhp at 3,000 rpm, 54 in. Hg at sea level
Normal rated	1,050 bhp at 2,600 rpm, 43 in. Hg at 10,000 ft
Military rated	1,180 bhp at 3,000 rpm, 52 in. Hg at 21,500 ft
Propeller (special Aeroproducts type)	
Diameter	11 ft 7 in.
Number of blades	4
Engine-propeller gear ratio	2.23:1
Fuel capacity (without belly tank), gal	136
Weight empty, lb	5, 910
Normal gross weight, lb	7, 650
Wing loading (normal gross wt.), lb/sq ft	30. 85
Power loading (normal gross wt., 1,050 bhp), lb/bhp	7. 29
Over-all height (taxying position)	11 ft 4 in.
Over-all length	32 ft 8⅜ in.
Wing:	
Span, ft	38.33
Area (including section through fuselage), sq ft	248
Airfoil section, root	NACA 66,2x-116
Airfoil section, tip	NACA 66,2x-216
Mean aerodynamic chord, in.	82.54
Leading edge M.A.C., inches behind L.E. root chord	6. 11
Aspect ratio	5. 92
Taper ratio	0. 5
Dihedral (35-percent chord, upper surface), deg	3. 67
Root incidence, deg	1. 30
Tip incidence, deg	−0. 45
Wing flaps (plain sealed type):	
Total area, sq ft	12. 9
Span along hinge line, each, in.	62. 38
Travel, down, deg	45
Ailerons:	
Span along hinge line, each, in.	120. 75
Area rearward of hinge center line, each, sq ft	8. 14
Fixed balance area, each, sq ft	4. 83
Location of inboard end of aileron, percent semispan	44. 2
Location of outboard end of aileron, percent semispan	96. 7
Travel, deg	±15
Horizontal tail:	
Span, in.	175
Total area, sq ft	46. 92
Stabilizer area, sq ft	34. 15
Total elevator area, sq ft	12. 77
Elevator area rearward of hinge center line, including tab, sq ft	9. 85
Elevator area forward of hinge center line, sq ft	2. 92
Elevator trim tab area, sq ft	0. 92
Distance elevator hinge center line to L.E. of M.A.C., in.	226. 28
Elevator travel from stabilizer, down, deg	15
Elevator travel from stabilizer, up, deg	35
Vertical tail:	
See table II.	

Calibrated airspeed corresponds to the reading of a standard Air Force-Navy airspeed indicator connected to a pitot-static tube free from position error.

TABLE II.—DIMENSIONS OF ORIGINAL AND ENLARGED VERTICAL TAILS TESTED ON SUBJECT AIRPLANE

	Original	Enlarged
Total height along hinge center line, in	78.87	94.62
Height above horizontal tail center line, in	62.00	77.75
Total area, sq ft	23.73	26.58
Fin area, sq ft	13.47	15.96
Total rudder area, sq ft	10.26	10.62
Rudder area rearward of hinge center line, sq ft	8.30	8.65
Rudder area forward of hinge center line, sq ft	1.96	1.97
Rudder *trim* tab area, sq ft	0.84	0.84
Distance from rudder hinge center line to L.E. of M.A.C., in	248.40	248.40
Fin offset from thrust axis, deg	0	0
Rudder travel, deg	±30	±30

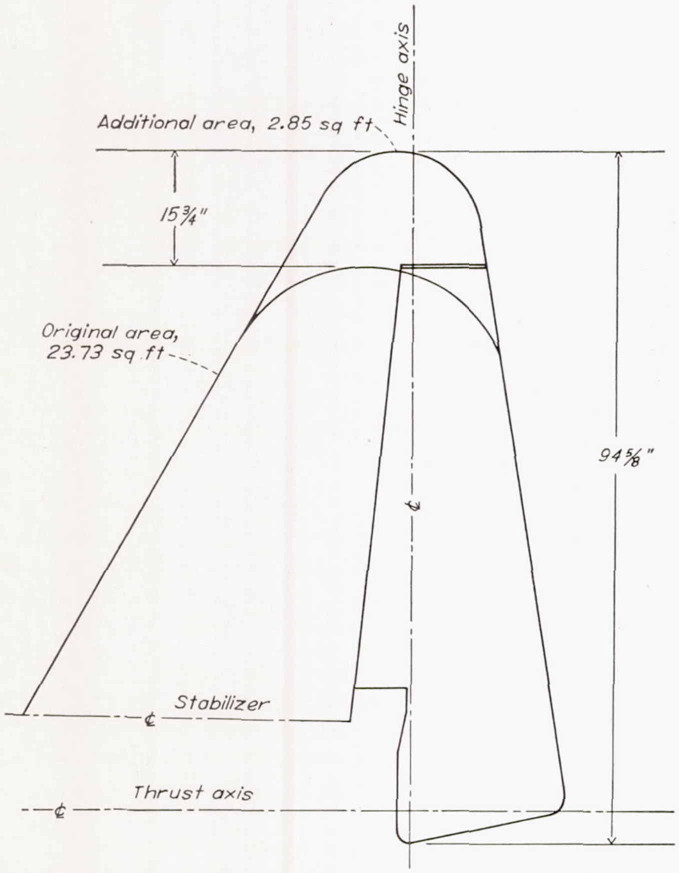


FIGURE 2.—Original and enlarged vertical tail surfaces tested on airplane.

The measurements of aileron and rudder angle were made by instruments connected directly to the respective control surfaces.

The sideslip angles were measured from a free-floating vane mounted on the end of a special boom extending about 1 chord length ahead of the left wing near the wing tip. No calibration was made of the possible position error of this installation; therefore, the absolute sideslip angles shown herein may be in error by about 1° to 2° because of possible outflow or inflow near the wing tips. Such errors are typical of similar installations on other similar airplanes. In spite of possible error in absolute sideslip angle, however, changes in

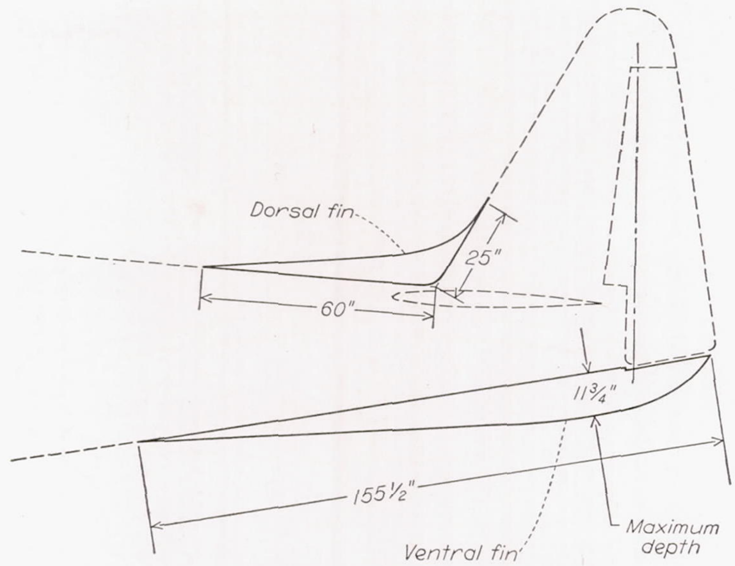


FIGURE 3.—Dimensional characteristics of dorsal and ventral fins. Dorsal-fin area, 2.11 sq ft; ventral-fin area, 7.21 sq ft.

FIGURE 4.—Detail view of dorsal fin.

sideslip angle measured at a given speed and normal acceleration are believed to be correct.

FLIGHT TESTS

The investigation consisted in determining the directional stability and control characteristics of the airplane with the various vertical-tail configurations from the following types of tests:

(1) Lateral oscillations
(2) Sideslips
(3) Rolls out of turns
(4) Rolls from pull-outs
(5) Trim changes due to speed changes
(6) Trim changes due to power changes

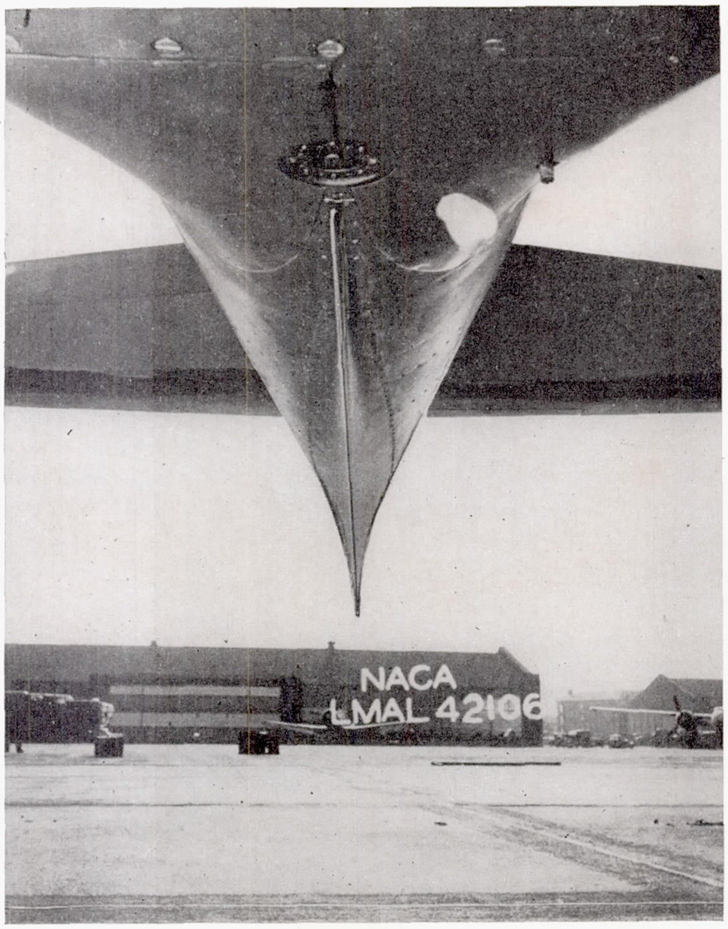


FIGURE 5.—Detail view of ventral fin showing sharp edge and cross section.

The airplane was in the clean condition (landing gear and flaps retracted) for all the tests.

The lateral oscillations were made by suddenly releasing all the controls after the airplane had been put into a small-angle steady sideslip. These runs were made using power for level flight at an altitude of 5,000 feet at indicated airspeeds of 150, 200, 250, and 300 miles per hour.

The sideslips were made by the continuous-recording technique that is described in detail in reference 1. The steady yawing and rolling velocities in the continuous sideslips were held sufficiently low to consider the resulting data representative of that which would be obtained in steady sideslips. Sideslips were made at an altitude of 5,000 feet with engine idling at 150 miles per hour and with normal rated power at 150 and 300 miles per hour and at an altitude of 25,000 feet with normal rated power at 150 miles per hour.

The rolls out of turns were made with engine idling at an altitude of 5,000 feet at speeds between 125 and 130 miles per hour (approx. 125 to 130 percent of the power-off stalling speed). For these tests, the airplane was first put into a steady banked turn with about 45° bank angle (corresponding to approx. $1.4g$ normal acceleration) and then the stick was moved abruptly to a predetermined lateral deflection against the direction of bank while the rudder was held fixed. The resulting roll was held until after the maximum sideslip angle had been obtained.

Rolls from pull-outs were made at an altitude of about 5,000 feet at speeds of 200, 250, and 300 miles per hour. In order to execute these maneuvers, the pilot rapidly pulled the airplane to $3g$ normal acceleration with wings laterally level and then abruptly applied a predetermined aileron stick deflection while the rudder was held fixed. Until the maximum sideslip angle was reached, the pilot attempted to hold the initial normal acceleration constant by movements of the elevator in accordance with indications of a visual accelerometer. For this series of tests, the propeller blade angle and thrust coefficient were held constant at the values determined by using normal rated power at an indicated airspeed of 300 miles per hour. Therefore, at the lower test speeds, both the engine speed and manifold pressure were reduced from the values corresponding to normal rated power (2,600 rpm, 43 in. Hg). The propeller blade angle and thrust coefficient were held constant in these tests in an attempt to maintain constant the contribution of the propeller to the directional stability of the airplane.

The directional trim changes due to speed changes were investigated only for the rated power condition at an altitude of approximately 5,000 feet for one rudder trim-tab setting. These tests were made by trimming the rudder force to zero in level flight (roughly 300-mph indicated airspeed) and then taking records in laterally level straight flight at steady speeds ranging from the stalling speed to indicated airspeeds of 450 to 470 miles per hour.

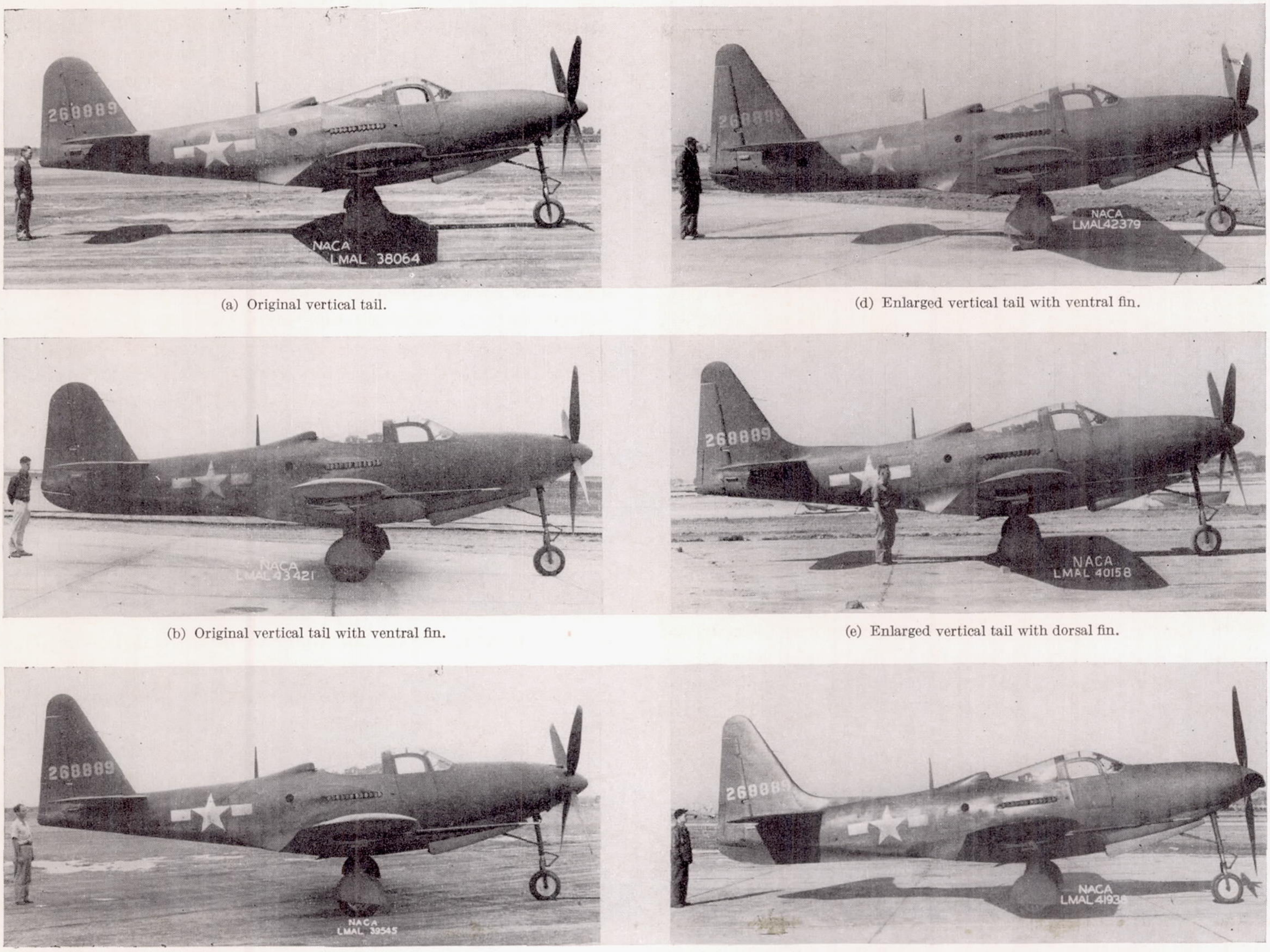
Directional trim changes due to power changes were determined at an altitude of 5,000 feet at indicated airspeeds of 125, 150, and 300 miles per hour. In making these tests the airplane was first trimmed for zero rudder force with rated power while the wings were held level in straight flight at the chosen speed. The throttle was then retarded to idle the engine. Records were taken after the initial flight speed, a laterally level attitude, and a straight flight path had been restored. The directional trim changes were also measured starting from the engine-idling trim condition.

RESULTS AND DISCUSSION

LATERAL-DIRECTIONAL OSCILLATION CHARACTERISTICS

Figure 8 shows a time history of an undamped lateral-directional oscillation which was encountered with the original vertical tail during a preliminary investigation of longitudinal stability characteristics and which was partly responsible for the present investigation. Upon noting a small amplitude periodic motion of the airplane during a routine climb to high altitude, the pilot fixed the controls to the best of his ability and obtained a record of the subsequent motion that failed to damp out. The minute control motions that actually occurred (fig. 8) are believed to be the result of the floating tendencies of the control surfaces coupled with control-system flexibility and possible play in the control systems rather than the result of stick or rudder pedal movements.

The oscillation appears on the surface to be a manifestation either of snaking, a continuous lateral-directional oscillation



(a) Original vertical tail.

(d) Enlarged vertical tail with ventral fin.

(b) Original vertical tail with ventral fin.

(e) Enlarged vertical tail with dorsal fin.

(c) Enlarged vertical tail.

(f) Enlarged vertical tail with dorsal and ventral fins.

FIGURE 6.—Vertical-tail configurations.

in which movements of the rudder reinforce the motion, or of Dutch roll, a continuous lateral-directional oscillation which occurs with rudder fixed. Of these two possibilities, the evidence appears to favor the Dutch roll supposition because the rudder movements which occur appear much too small to account for the 2° to 3° change in sideslip angle involved. The occurrence of Dutch roll would indicate insufficient directional stability in the case of this airplane because the dihedral effect, though positive, is not strong.

The fact that the continuous oscillation was not encountered in the present series of tests even though all the airplane conditions were the same with the exception of the longitudinal stability was noteworthy and suggests the possibility that the continuous oscillation may have been related to coupling of the longitudinal and directional motions through the gyroscopic reactions of the propeller.

A summary of the lateral-directional oscillation characteristics determined in the investigation is given in figure 9. All the results of figure 9 were obtained from time histories of the variation in sideslip angle. The time required for the oscillation to damp to half-amplitude was measured directly from envelope curves drawn on the curves of sideslip angle plotted against time. In general, each test point shown in figure 9 is an average of two to four separate determinations.

The results of figure 9 show that the addition of the ventral fin to the original vertical tail caused an appreciable decrease in the period, particularly at higher speeds. This decrease in period indicates an appreciable increase in directional stability. However, the increased aspect ratio brought about by the addition to the tip of the original vertical tail caused an even greater decrease in period at all speeds; thereby greater increases in directional stability are indicated. It may be noted that additions of ventral- and dorsal-fin area to the enlarged vertical tail did not bring about pronounced changes in period, particularly at higher speeds. Therefore, it appears that low-aspect-ratio fins such as the

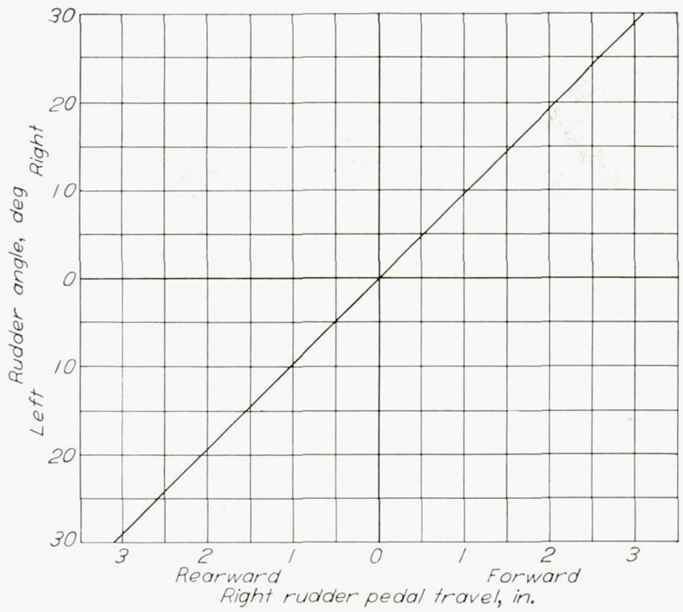


FIGURE 7.—Variation of rudder angle with position of right rudder pedal. Rudder-pedal moment arm 10¾ inches. Pedal travel measured along arc.

ventral fin tested may be reasonably beneficial to directional stability when the initial directional stability is meager but relatively ineffective when the initial directional stability is good. This view is substantiated by the data obtained in the other types of directional stability tests as is shown subsequently. The data indicate that the dorsal and ventral fins were, in general, more effective in improving the damping of the lateral oscillations than was the addition of tip area to the original vertical tail. Such a result appears reasonable in view of the probable effects of the different modifications on the effective dihedral of the airplane.

The lateral-directional-oscillation data have been plotted as the time to damp to half-amplitude against period in figure 10. The boundary between satisfactory and unsatisfactory characteristics according to reference 2 has been included for comparative purposes. All the data lie well within the satisfactory side of the boundary and these results agreed with pilots' opinions of the damping of the oscillations. The pilots believed, however, that the lateral-directional-oscillation tests did not show up the differences in directional stability that were apparent when flying the different configurations in the other types of maneuvers, such as the rolls from turns and pull-outs.

SIDESLIP CHARACTERISTICS

The results of the sideslip tests are shown in figures 11 to 13. Note that in these figures and in a few subsequent figures some of the faired curves have been repeated several times to facilitate an evaluation of the effect of the various modifications on the directional characteristics. More specifically, the plots at the top of each figure are designed to show the effect of increasing aspect ratio of the vertical tail and, to a lesser extent, increasing vertical tail area; the next set of curves shows the effect of adding the ventral fin to the original vertical tail, and the remaining plots show the effect of adding the ventral and dorsal fins to the enlarged vertical tail.

The data obtained for both the engine-idling and the rated-power conditions at 150 miles per hour at an altitude of 5,000 feet are shown in figure 11. In the top plot of figure 11 (a), when the aspect ratio and vertical-tail area were increased, a definite increase in slope of the curve of rudder angle plotted against sideslip angle occurred. Measurements of the slopes of these curves at zero sideslip angle result in values of 0.72 and 1.04 for the original and enlarged vertical tails, respectively. On a percentage basis, the slope of the curve for the enlarged vertical tail is about 144 percent of the slope for the original vertical tail. When the relative effectiveness of the two vertical tails and rudders (as estimated from the dimensions of tables I and II and the charts of reference 3) is considered, however, it can be shown that these slope values indicate the enlarged vertical tail provided about 194 percent of the rudder-fixed directional stability supplied by the original vertical tail. This greater relative increase in directional stability over the increase in slope of the curves of rudder angle against sideslip angle is due primarily to the higher lift-curve slope of the enlarged vertical tail resulting from the large increase in aspect ratio. The effect of adding the ventral fin (fig. 11 (a)) was to increase the directional stability primarily at high sideslip angles. The ventral fin again caused a greater increase in directional stability when used with the original vertical tail than when used with the enlarged vertical tail. The addition of the ventral fin to the original vertical tail or the addition of either the ventral or the dorsal fin to the enlarged vertical tail caused a marked steepening of the curves of pedal force against sideslip angle at large angles of sideslip; this trend is characteristic of the effect of such fins and results from the increase in rudder-fixed directional stability contributed by the fins at high angles of sideslip.

With normal rated power at 150 miles per hour (fig. 11 (b)), the airplane exhibited strong tendencies toward rudder-force reversal at large angles of sideslip both in left and in right sideslip with either the original or enlarged vertical tails. Actual rudder-force reversals were encountered in left sideslip for both configurations, but the data are not shown because of unsteadiness in the airplane motion which occurred at very large angles of sideslip. The pilot reported that when a left sideslip angle of approximately 25° was reached, the rate of yawing seemed to increase precipitously without further movement of the rudder pedals. In one particular run with the original vertical tail, a left sideslip angle of 35° was attained before recovery was effected. This undesirable characteristic was believed to be caused by the combination of rudder overbalance and great flexibility of the control system. During a slow increase in sideslip angle, as the rudder force was relieved at large sideslip angle because of the usual large negative rudder floating tendency, the rudder automatically moved farther without a corresponding movement of the rudder pedals inasmuch as the deflected control system was returning to an unstressed condition. From the data shown in figures 7 and 11 (b), it has been estimated that the rudder would move approximately 6° with the rudder pedals fixed for a rudder hinge-moment change corresponding to a 100-pound change in rudder pedal force. When the ventral fin was used with the original vertical tail or when either the ventral or the dorsal fin or a com-

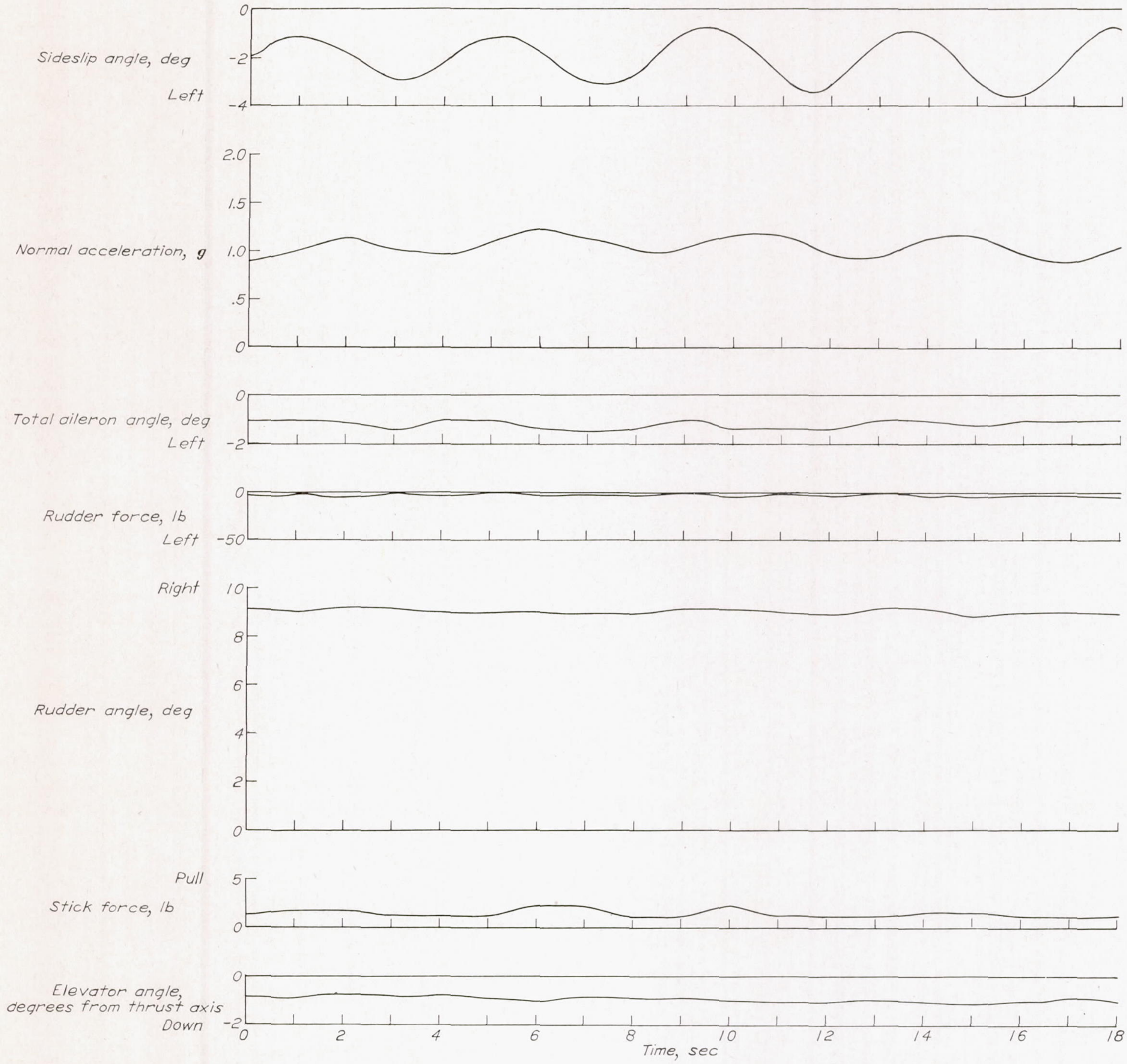


FIGURE 8.—Time history of undamped directional oscillation which occurred in steady climb at about 150 miles per hour at an altitude of 22,000 feet. Normal rated power. Original vertical tail. Pilot attempted to hold all controls rigidly fixed while obtaining this record.

bination of the two was used with the enlarged vertical tail, the rudder-force reversal was eliminated and the rudder pedals could be deflected fully against the stops in the pilot's compartment without encountering any precipitous yawing tendency. In the absence of rudder-force reversal, the relatively great flexibility of the rudder control system was not objectionable. Figure 11 (b) shows that the use of both the dorsal and ventral fins with the enlarged vertical tail caused a marked increase in both rudder-fixed and rudder-free directional stability in low-speed, high-power conditions of flight.

Figure 12 presents the data obtained in sideslips at an indicated airspeed of 300 miles per hour at an altitude of 5,000 feet with normal rated power (2,600 rpm, 43 in. Hg). The data show that for the small ranges of sideslip angles covered addition of the ventral fin to either the original or enlarged vertical tail had no appreciable effect on the slopes of the curves of rudder angle or rudder force against sideslip angle; whereas the addition of the dorsal fin to the enlarged vertical tail had a slightly beneficial effect on the slopes. However, the top curves of figure 12 show that increasing the aspect ratio and area of the original vertical tail brought

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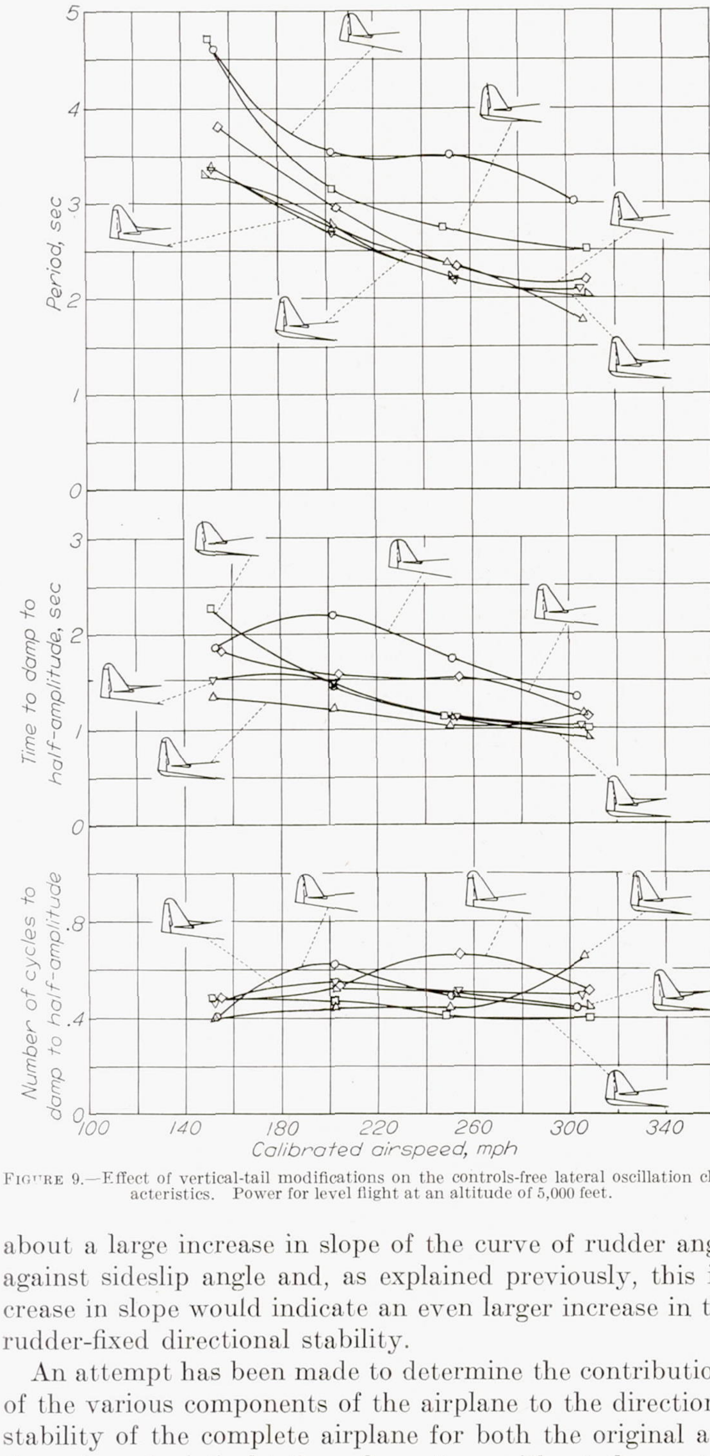


FIGURE 9.—Effect of vertical-tail modifications on the controls-free lateral oscillation characteristics. Power for level flight at an altitude of 5,000 feet.

about a large increase in slope of the curve of rudder angle against sideslip angle and, as explained previously, this increase in slope would indicate an even larger increase in the rudder-fixed directional stability.

An attempt has been made to determine the contributions of the various components of the airplane to the directional stability of the complete airplane for both the original and the enlarged vertical-tail configurations without the ventral or the dorsal fin. The results of these estimations are given in table III in terms of the variation of yawing-moment coefficient with sideslip angle C_{n_β}. In making these estimations, the dynamic pressure at the tail was assumed to be equal to the free-stream dynamic pressure. This assumption should be nearly correct for the speed condition for which data are shown in figure 12.

Table III shows that the directional stability of the two configurations calculated primarily from the airplane dimensions and charts (item 4) was appreciably greater than that estimated primarily from the flight data (item 5). Hence, there is shown an unaccounted-for loss in directional stability (item 6) which was the same for both configura-

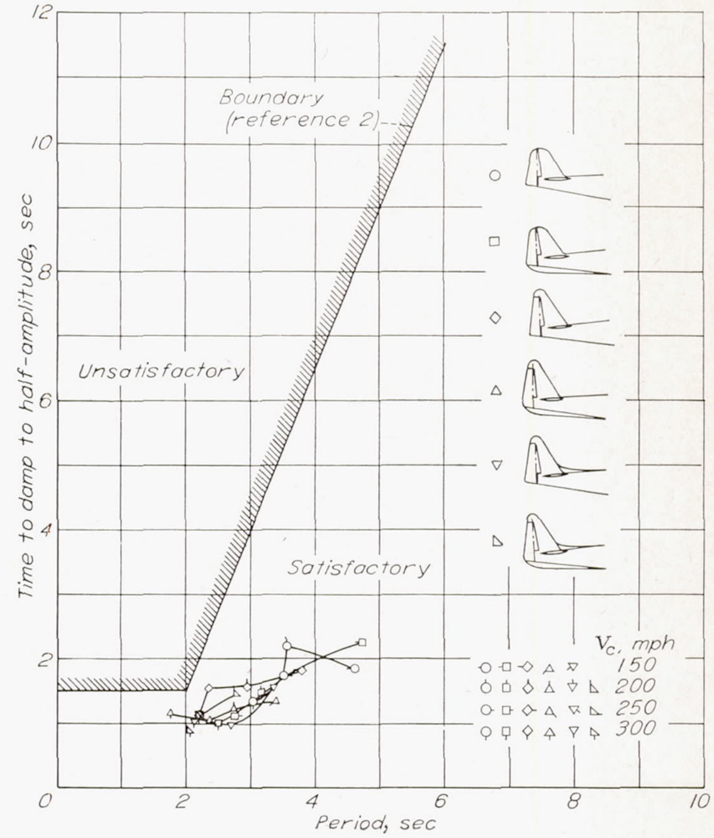
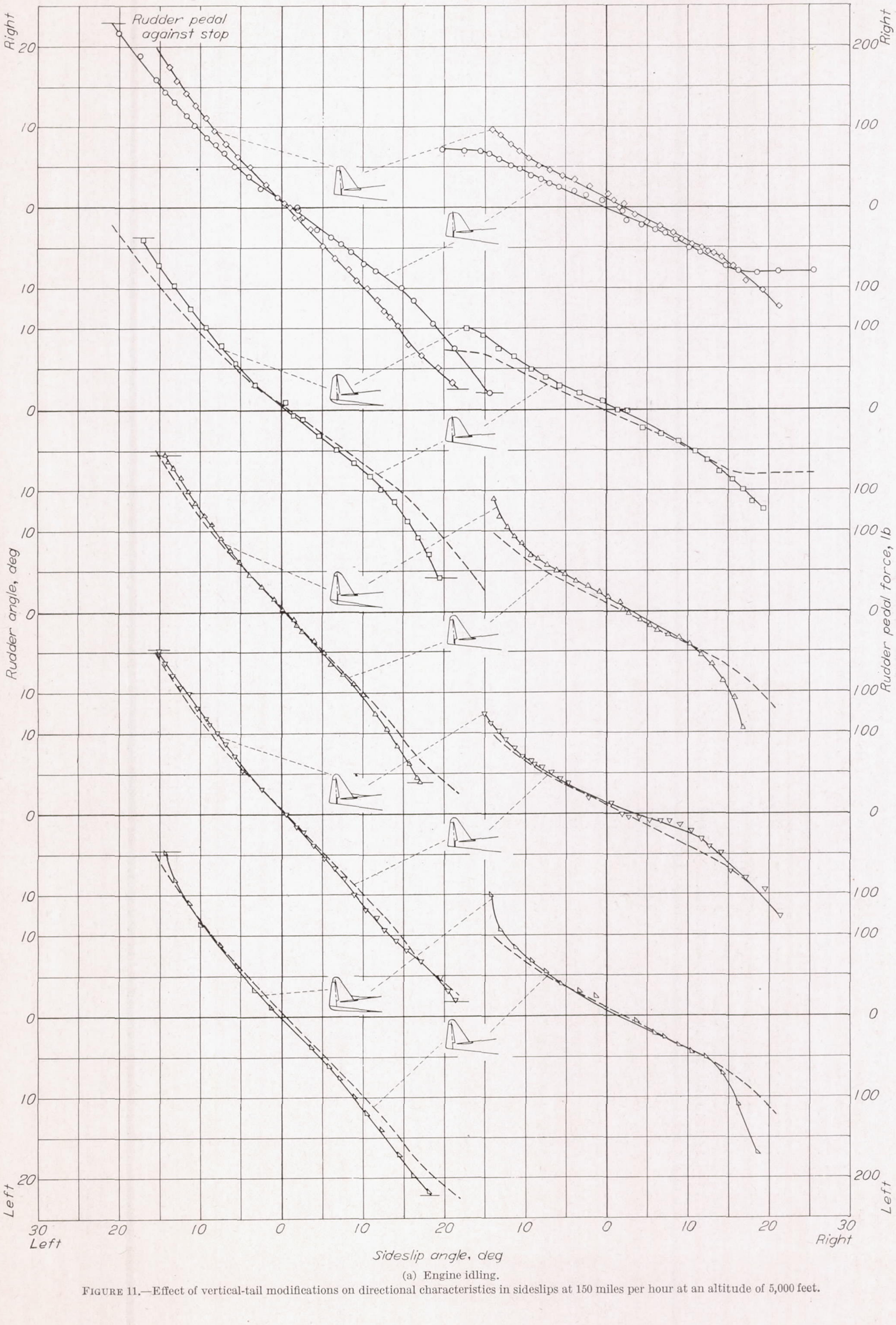


FIGURE 10.—Time to damp to half-amplitude as a function of period of the lateral-directional oscillations.

tions. The unaccounted-for destabilizing increment probably can be attributed to sidewash or interference effects, to loss in dynamic pressure at the tail, or to inability to predict accurately the lift-curve slopes of the vertical tails. In connection with the last-named item, recent unpublished test data indicate that the lift-curve slopes given by reference 3 are approximately 10 percent too high. Use of lower values for the lift-curve slopes would reduce the magnitude of the unaccounted-for losses in the calculations of table III

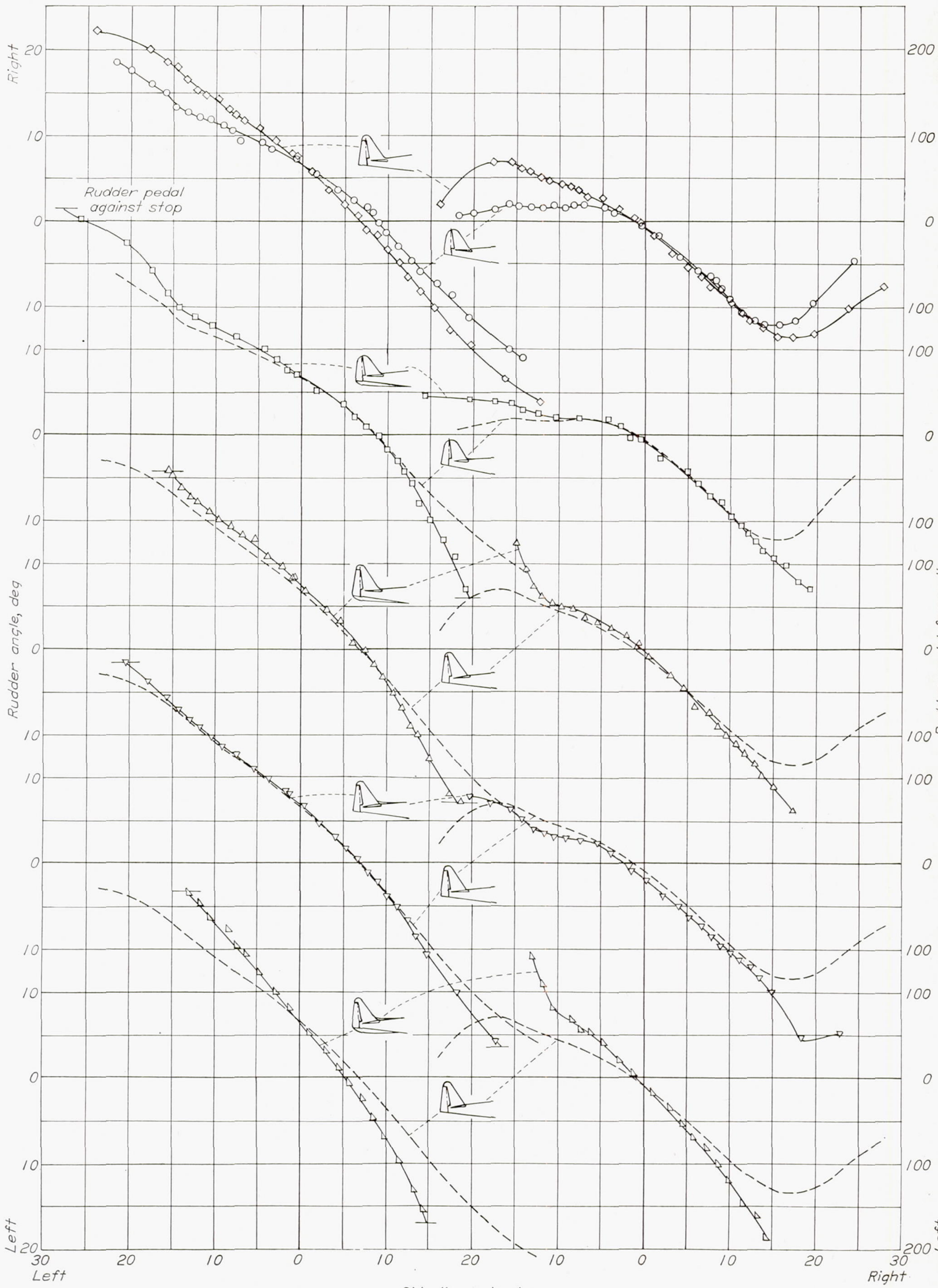
TABLE III.—ESTIMATED CONTRIBUTIONS OF VARIOUS AIRPLANE COMPONENTS TO DIRECTIONAL STABILITY OF PROPELLER-DRIVEN FIGHTER AIRPLANE

Item	Component	C_{n_β}, per degree		Source
		Original vertical tail	Enlarged vertical tail	
1	Vertical tail	0.00192	0.00260	Calculated from airplane dimensions and charts of reference 3 assuming no sidewash or interference effects.
2	Fuselage and wing	−.00040	−.00040	Wright Field wind-tunnel data.
3	Propeller	−.00060	−.00060	Estimated from propeller dimensions and charts of reference 4.
4	Complete airplane (calculated neglecting sidewash, interference, and so forth).	.00092	.00160	Sums of items 1, 2, and 3.
5	Complete airplane (estimated from flight data at 300 mph).	.00058	.00127	Product of item 1, estimated rudder effectiveness from figure 4 of reference 3, and measured slope of rudder angle plotted against sideslip angle from figure 12.
6	Unaccounted for (sidewash, interference, and so forth).	−.00034	−.00033	Item 5 minus item 4.



(a) Engine idling.

FIGURE 11.—Effect of vertical-tail modifications on directional characteristics in sideslips at 150 miles per hour at an altitude of 5,000 feet.



(b) Normal rated power (2,600 rpm, 43 in. Hg, approx. 1,050 bhp).

FIGURE 11.—Concluded.

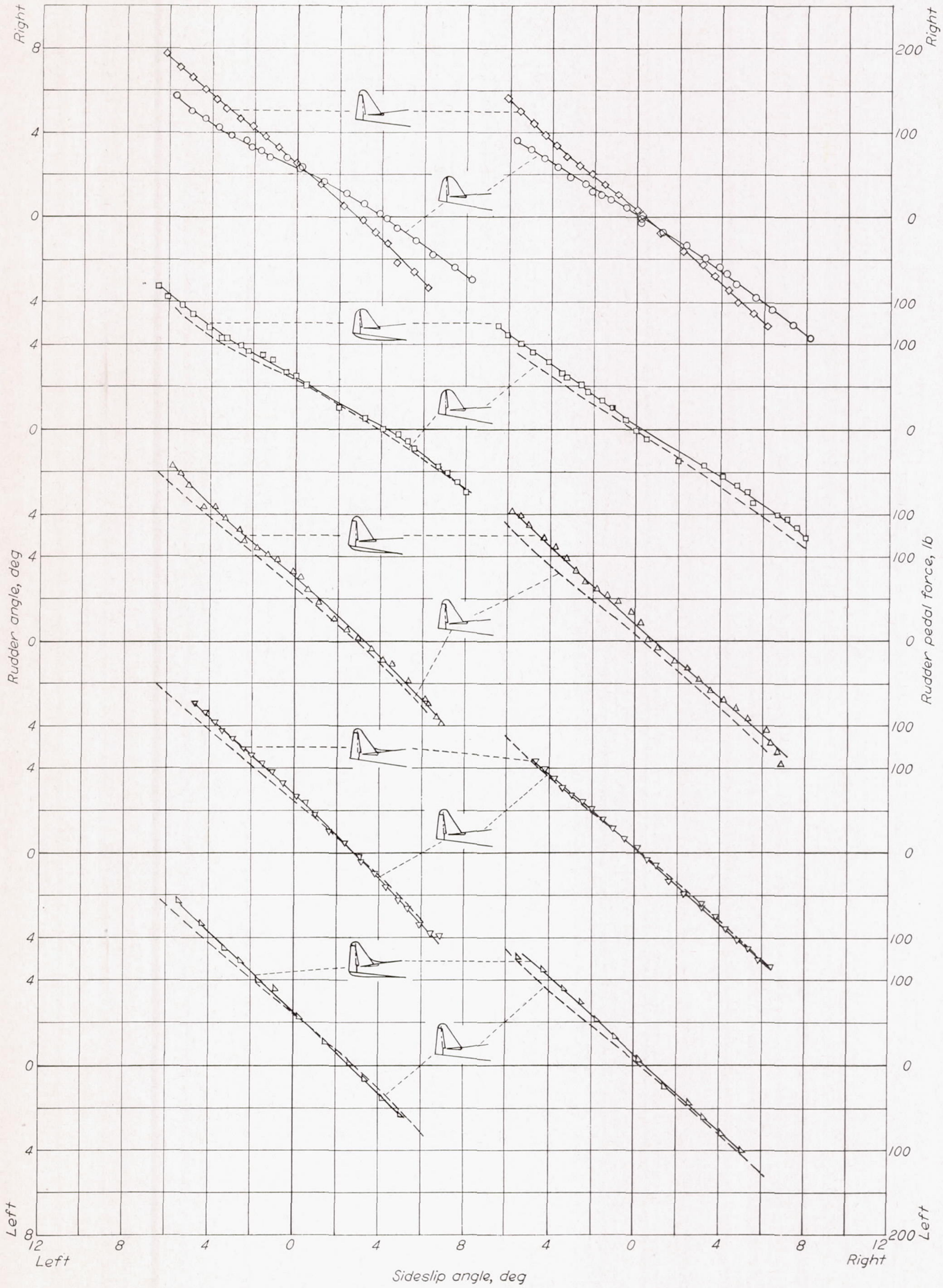


FIGURE 12.—Effect of vertical-tail modifications on directional characteristics in sideslips at 300 miles per hour at an altitude of 5,000 feet. Normal rated power (2,600 rpm, 43 in. Hg, approx. 1,050 bhp).

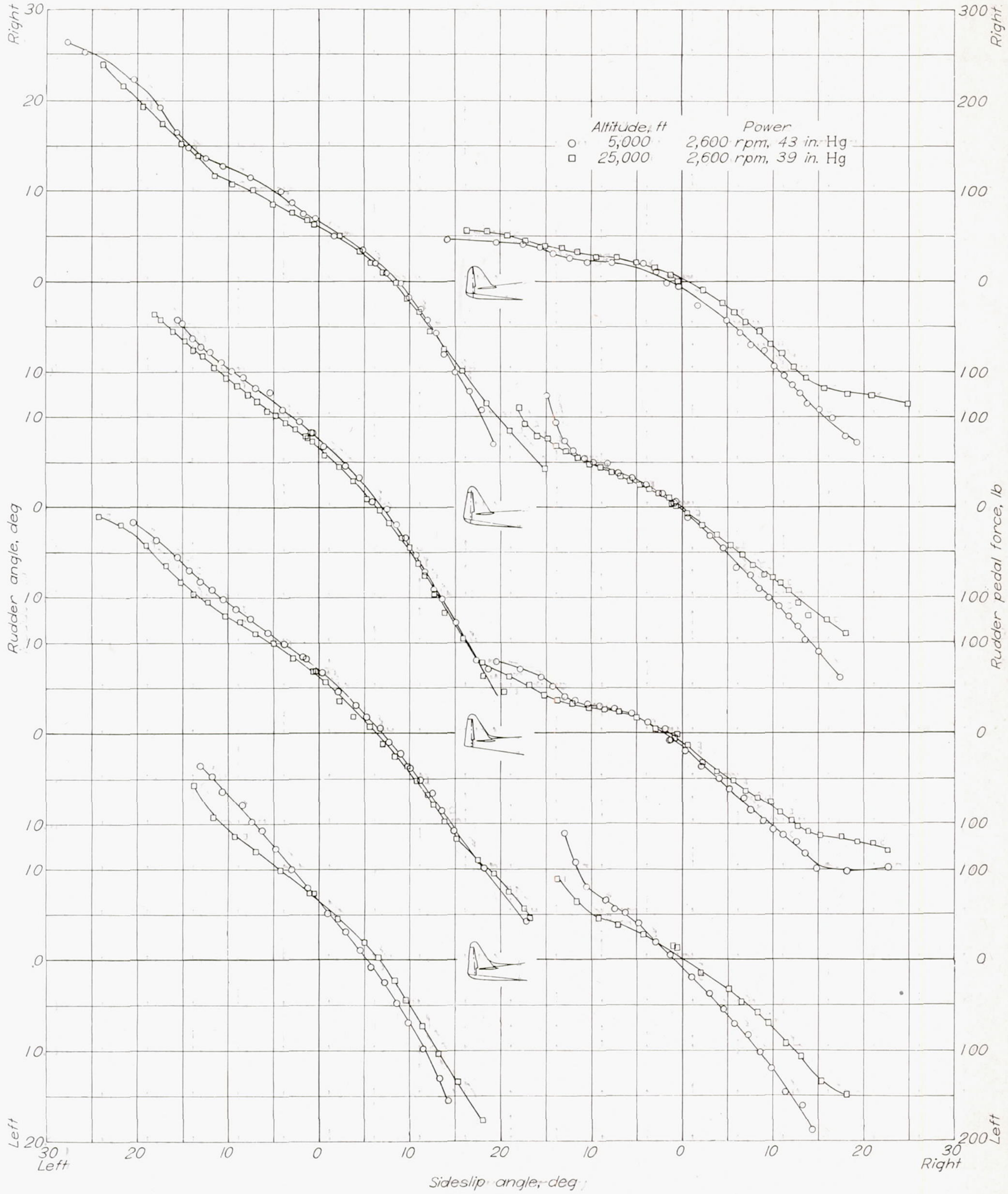


FIGURE 13.—Effect of altitude on the directional characteristics in sideslips at 150 miles per hour. Normal rated power.

Consideration of table III leads to the conclusion that the directional stability of the airplane with the enlarged vertical tail was approximately twice as great as that of the airplane with the original vertical tail. The value of C_{n_β} found from the flight data for the enlarged-tail configuration was 0.00127 and that for the original-tail configuration was 0.00058. This large increase in directional stability was accomplished by only a 12-percent increase in total vertical-tail area which was, however, disposed in such a way as to give the greatest practical increase of aspect ratio.

Figure 13 shows the effect of increasing altitude on the directional stability characteristics with normal rated power at an indicated airspeed of 150 miles per hour for four different airplane configurations. The consistent small decrease in directional stability with increasing altitude, shown by this figure, was believed to be attributable to the increased propeller blade angles that were required at the high altitude to produce the higher true airspeed corresponding to the same indicated airspeed used in tests at the low altitude. Reference 4 shows that increasing the blade angle increases the destabilizing contribution of a tractor propeller.

CHARACTERISTICS IN ROLLS OUT OF TURNS

Results of the rudder-fixed rolls out of turns are shown in figure 14. The data are plotted in terms of the maximum change in sideslip angle per unit airplane normal-force coefficient, rather than as simply the maximum change in sideslip angle, against aileron deflection. This procedure was followed in order to take into account the small changes in normal acceleration that unavoidably occur between the time the ailerons are abruptly deflected and the time the maximum sideslip angle is obtained. Theory shows that the yawing moment due to aileron deflection and rolling and, hence, the maximum sideslip angle attained depends primarily on the airplane normal-force coefficient. Consequently, in order to put the test results on a sound theoretical basis, each test run was analyzed to determine the ratio of the maximum change in sideslip angle which occurred to the average airplane normal-force coefficient which existed during the run. For purposes of computing the average airplane normal-force coefficient, the average normal acceleration and speed that existed during each run was used. If it is desired to obtain the actual sideslip-angle changes from the data of figure 14, the ordinate should be multiplied by the airplane normal-force coefficient for which the change in sideslip is desired. When using the data in this way, however, it must be recognized that the data of figure 14 apply only to high angles of attack, low speeds, and the engine-idling condition. Also, for very large sideslip-angle changes (larger than about 20°), the data tend to be of only academic interest because in the flight tests it was found that, by the time such large sideslip changes were attained, the airplane had rolled into a

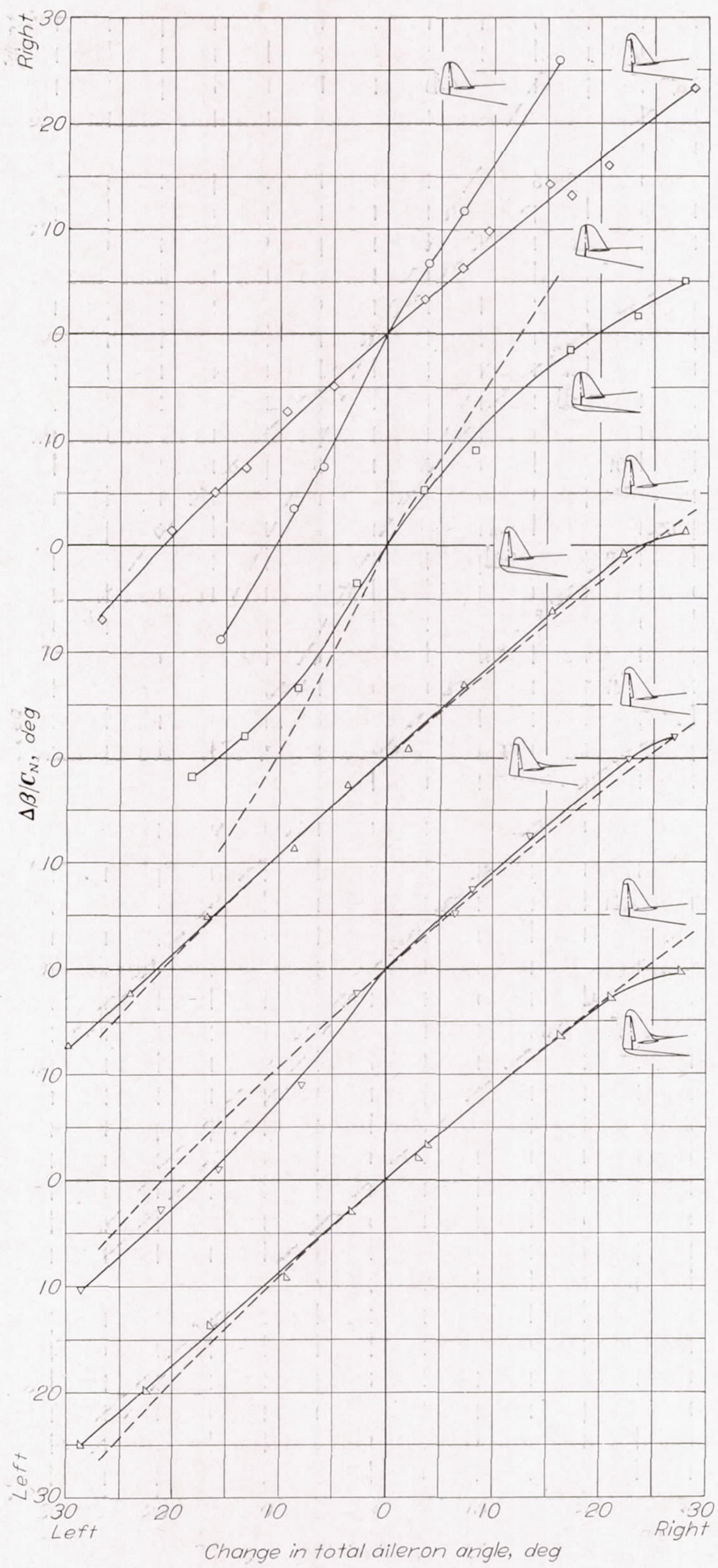


FIGURE 14.—Effect of various vertical-tail modifications on the ability to restrict yaw due to ailerons in rudder-fixed rolls out of turns at 125 to 130 miles per hour with engine idling. Ratio $\frac{\Delta\beta}{C_N}$ is maximum change in sideslip angle per unit airplane normal-force coefficient.

near-inverted attitude in spite of the advantage obtained by starting the rolls from a 45° banked position. When such large changes in attitude occur, the effect of gravity may be important in determining the maximum sideslip angle reached.

The top plot of figure 14 shows that approximately twice as much change of sideslip angle occurred with the original vertical tail than with the enlarged vertical tail for a given aileron deflection. These results indicate that the directional stability of the airplane was approximately doubled by the enlarged vertical tail. Addition of the ventral fin to the original vertical tail (fig. 14) brought about a moderate increase in directional stability for small changes in sideslip angle and, large increases for large changes in sideslip angle. The effect of the ventral fin was negligible when used with the enlarged vertical tail. These trends are in general agreement with those obtained from the low-speed sideslip tests previously discussed. Addition of the dorsal fin to the enlarged vertical tail apparently reduced the ability of the vertical tail to restrict the yaw due to aileron deflection in left rolls, but no detrimental effects of the dorsal fin appeared when the ventral fin also was installed. This peculiar effect of the dorsal fin occurred also in the higher speed rolls from pull-outs (fig. 15). No explanation for the effect has been found.

CHARACTERISTICS IN ROLLS FROM PULL-OUTS

Previous work on the propeller-driven fighter airplane (reference 5) has shown that the roll-from-pull-out maneuver is one in which very large vertical-tail loads may be encountered. The magnitude of such vertical-tail loads was shown to depend to some extent on the directional stability of the airplane. Increasing the directional stability of the airplane would be expected to reduce the maximum vertical-tail load because, for a given yawing moment due to application of ailerons, the maximum sideslip angle reached is reduced; the vertical-tail load required to offset the unstable yawing moments of the fuselage and propeller is therefore reduced even though the load required to offset the primary yawing moment due to rolling remains essentially constant with varying directional stability

The results of the rolls from pull-outs at the various speeds tested are shown in figure 15. The faired curves of the top plot indicate that, on the average, the airplane yawed only about 60 percent as much with the enlarged vertical tail as it did with the original vertical tail for a given aileron deflection. The addition of the ventral fin to the original vertical tail increased the yaw due to use of the ailerons for left rolls. This result is contrary to that obtained at low speed with the engine idling (fig. 14) and might possibly be caused by a local increase in unfavorable sidewash in the region of the ventral fin brought about by the use of power.

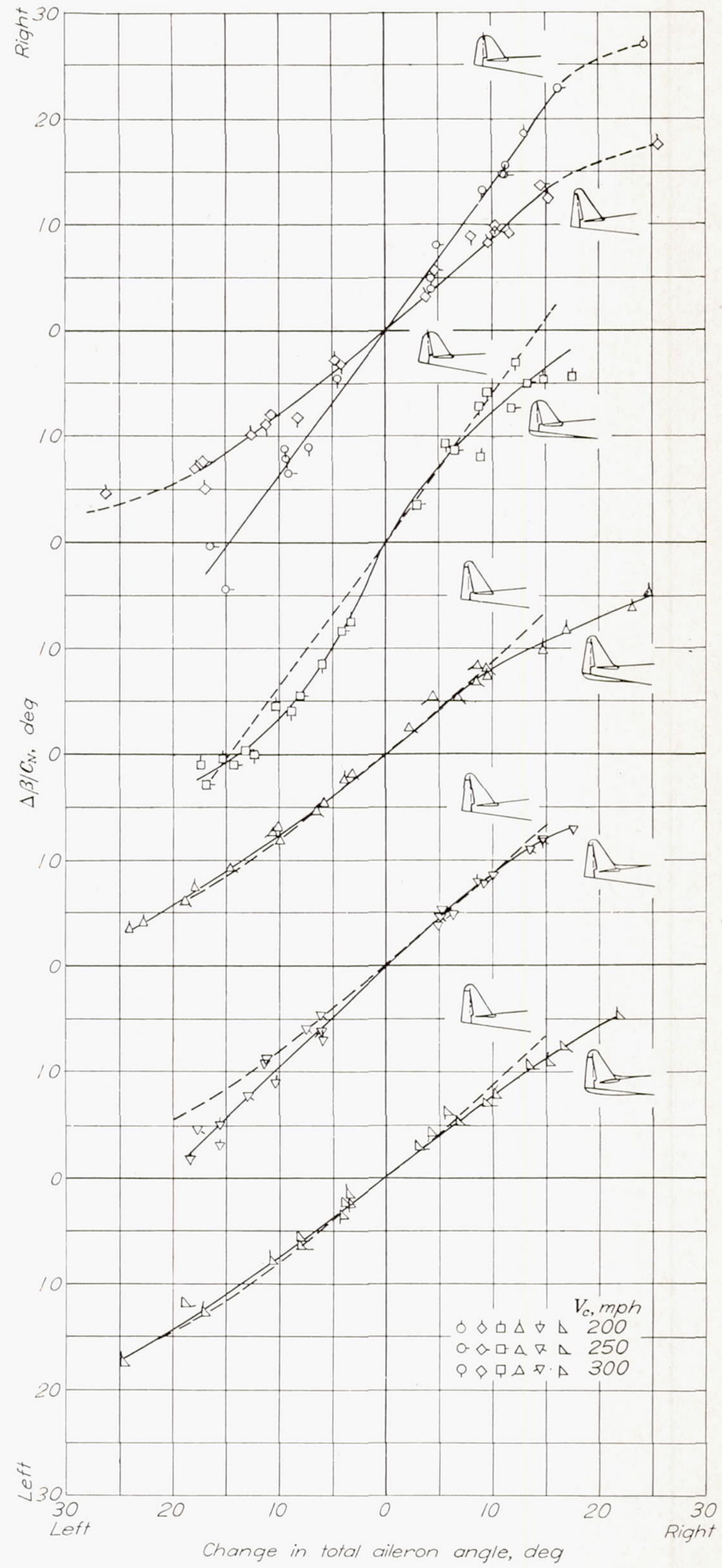


FIGURE 15.—Effect of vertical-tail modifications on the ability to restrict yaw due to ailerons in abrupt rudder-fixed rolls from 3g pull-outs at various speeds. Propeller blade angle and thrust coefficient held constant at values determined by using normal rated power (2,600 rpm, 43 in. Hg) at 300 miles per hour. Altitude approximately 5,000 feet.

Use of the ventral fin with the enlarged vertical tail, however, was not detrimental to the characteristics in left rolls; therefore, any attempts to explain the effects of the ventral fin on the basis of sidewash must be regarded as conjecture. As would be expected, the data of figure 15 show that the configuration incorporating all the modifications provided the greatest directional stiffness for restricting the yaw caused by the yawing moment due to aileron deflection and rolling.

DIRECTIONAL TRIM CHARACTERISTICS

Typical variations of sideslip angle and rudder angle required for laterally level straight flight throughout the speed range with rated power for the enlarged vertical tail are shown in figure 16. Similar sideslip-angle and rudder-angle data for the other five configurations tested were almost identical to those shown in figure 16 and are therefore not presented. Only about 20° right rudder deflection was required at the stalling speed so that directional control power was adequate. A center-of-gravity movement of 5 percent of the mean aerodynamic chord had a negligible effect on the directional trim characteristics as shown in figure 16.

Variations of the rudder pedal force for wings-level trim with indicated airspeed are shown in figure 17 for the six vertical-tail configurations tested. The various vertical-tail modifications are seen to have a slight but definite effect on the pedal-force variations at high speeds. The shape of the curve for the original vertical tail is characteristic of that which might be expected if the rudder fabric covering or the rudder structure were distorted owing to high aerodynamic loads, whereas the shape of the curve for the enlarged vertical tail with both dorsal and ventral fins added is approximately that which might be expected without rudder distortion. With regard to the desirability of the various types of force variations with speed shown in figure 17, there appears to be little to choose from in view of the fact that all the configurations provided desirably small changes in rudder force with changes in speed.

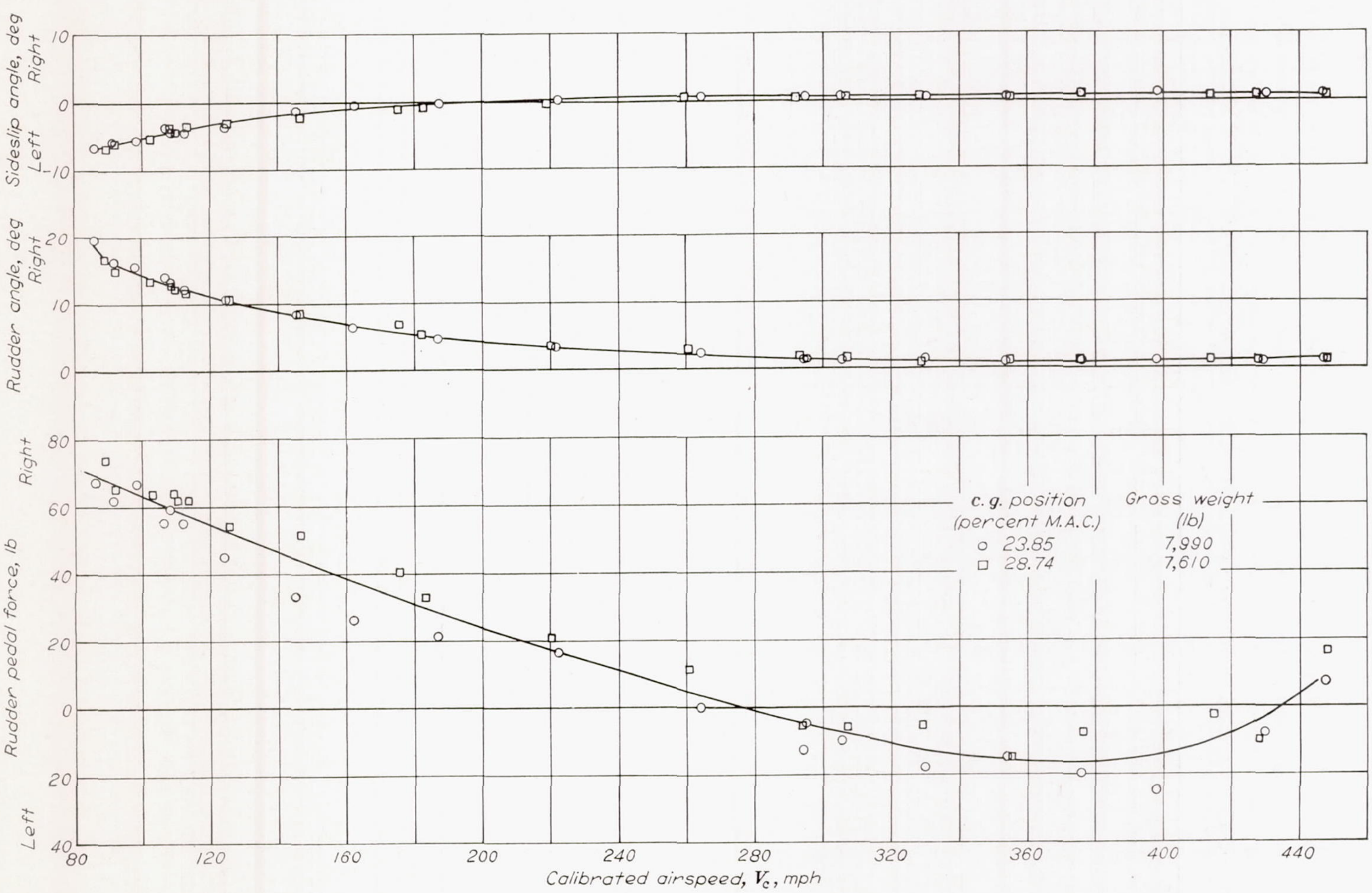


FIGURE 16.—Data showing typical variations of rudder angle and sideslip angle with airspeed for straight, wings-level flight. Enlarged vertical tail surface. Clean condition; normal rated power (2,600 rpm, 43 in. Hg); altitude, 5,000 feet.

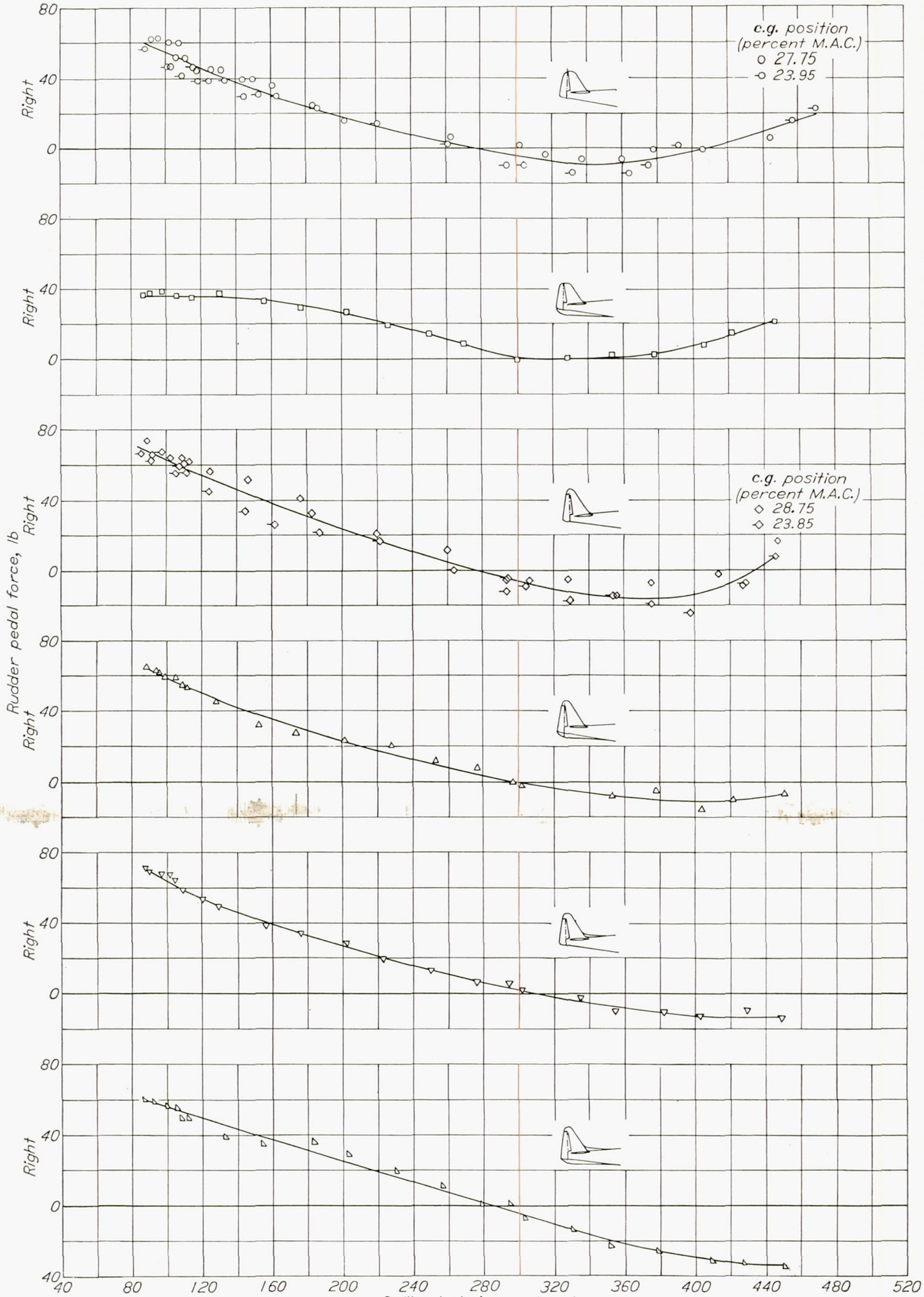


FIGURE 17.—Effect of vertical-tail modifications on the variation of rudder force with speed for constant trim tab setting. Normal rated power (2,600 rpm, 43 in. Hg); altitude, 5,000 feet.

TRIM CHANGES DUE TO POWER CHANGES

The effect of the various vertical-tail modifications on the trim changes due to power changes is shown in figure 18. The data show that the addition of the ventral fin to the original tail or the addition of either the dorsal or the ventral fin to the enlarged vertical tail had a negligible effect on the rudder-angle trim changes due to power changes. On the other hand, considerably more change in rudder angle was required to offset the yawing moment due to power for all the enlarged vertical-tail configurations than for either of the original vertical-tail configurations, particularly at low speeds. This result is believed to be explained by the difference in height of the two vertical tails as related to the relative twist of the slipstream. At low speeds (high angles of attack) the fixed tip of the enlarged vertical tail probably extended into a region of the slipstream where the cross-flow change due to power change was greatest. Therefore, in order to offset the increased change in yawing moment due to cross flow of the slipstream, greater rudder-angle changes were required with the taller, enlarged vertical tail than with the original vertical tail. The rudder-pedal-force change with power change was approximately constant over the speed range tested, and this change was desirably small inasmuch as it amounted to only about 50 pounds for any of the configurations tested.

PILOTS' OPINIONS

As noted previously, the airplane with the original vertical tail showed undesirable directional characteristics that included (1) excessive yawing in abrupt aileron rolls, (2) rudder-force reversals in low-speed high-engine-power sideslips, (3) an undamped directional oscillation of small amplitude that sometimes occurred in the rated-power climb condition, and (4) inadvertent sideslipping in accelerated maneuvers which led to difficulty in maintaining constant normal acceleration. The pilots considered all the foregoing characteristics unsatisfactory.

Following the installation of the enlarged vertical tail and the ventral and dorsal fins, four pilots, all of whom had had wide experience in flying airplanes of many different types, were asked to evaluate the directional stability and control characteristics of the airplane through its usual flight range. These evaluation flights were made in January 1945. Written comments from two of the pilots were obtained and their

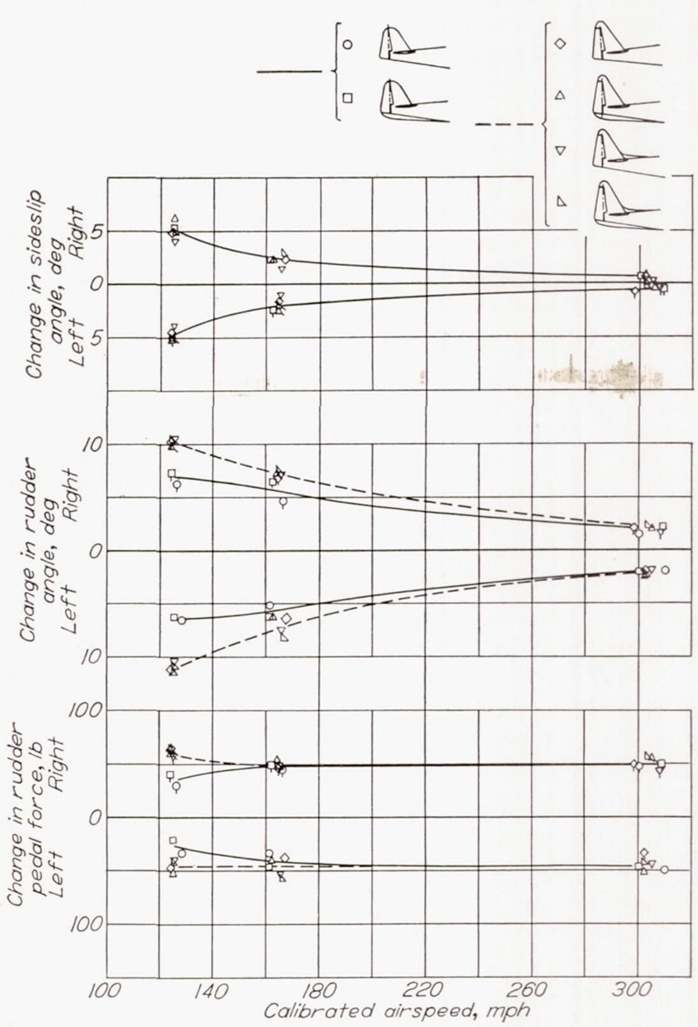


FIGURE 18.—Effect of vertical-tail modifications on the rudder trim changes due to power changes at an altitude of 5,000 feet. Flagged symbols indicate power off to rated power and symbols without flags indicate rated power to power off.

opinions are indicated in the following discussion:

Pilot A:

With normal rated power (2,600 rpm, 43 in. Hg), pilot A reported that the rudder-force characteristics in steady right or left sideslip were satisfactory in both landing and clean configurations. No overbalance or lightening of rudder pedal forces was encountered at any speed, 120 miles per hour being the minimum speed at which steady sideslips were made. At low speeds full rudder was obtained, but at high speeds (above approx. 200 mph) force limited the deflection obtainable. Force variation with sideslip was not considered excessive. With power off, the force characteristics were considered to be satisfactory in both landing and clean configurations.

The directional oscillation was considered to be satisfactorily and heavily damped in all cases.

Pilot A considered that the rudder trim-force variation with speed and power was better than in most current fighters although it was not ideal and appeared to have been affected somewhat by vertical-surface changes. In the worst case the trim change probably fell within the specified 200-pound limit. With the tab at a setting for trim in climb, cruise, or high speed (about 0°), probably no more than a 100-pound left or right rudder force was required for any condition from stalling speed to 450 miles per hour. Trim change through the range 1.5 to 1.0 times the stalling speed, particularly with power on, was higher than through higher speed ranges.

The maneuvering characteristics were considered to be excellent. With rudder fixed or free, rapid rolls could be made at any speed without appreciable yawing even at low speed with rated power. Greatest adverse yawing occurred in rolls in the wave-off condition at low speed but this yawing was easily overcome by use of the rudder. Pilot A considered this airplane the best he had ever flown for ease of directional control in manuvering flight and for all-around directional stability and control characteristics.

Pilot B:

Pilot B considered the directional stability to be excellent both at high and low altitudes. Adverse yaw due to use of ailerons was low, and at 125 miles per hour at an altitude of 25,000 feet turns using full aileron deflection could be made with rudder locked with only a mild, but well-damped, lateral oscillation developing. When using rudder in the same maneuver, pilot B used too much rudder and developed the oscillation anyway. Pitch due to yaw in these manuevers was negligible and the normal acceleration could be controlled accurately. From rudder kicks in rated power climb and at high speed at 25,000 feet, the lateral oscillations were damped after 2 cycles. In rated-power sideslips at 150 miles per hour at 25,000 feet, control was positive all the way to full rudder deflection with high rudder forces at full deflection with only a very slight rudder buffet. Bank angle was high. Directional control at high speed was positive without uncontrolled oscillations developing from small rudder motions. In pull-ups or push-downs at 25,000 feet, yawing due to propeller gyroscopic couples was not noticeable unless the directional gyroscope was watched. At no time was there any indication that the airplane was undesirably stiff directionally. In all rapid turns using ailerons and rudder, pilot B overused the rudder, and therefore considered this to indicate low adverse yawing and a light rudder. The rudder trim-force changes with speed were desirably light.

Pilot B could detect little change in directional characteristics between high and low altitudes and considered this airplane to be the best he had ever flown at high altitudes.

CONCLUSIONS

From an investigation of the effect of various vertical-tail modifications on the directional stability and control characteristics of a propeller-driven fighter airplane, the following conclusions were indicated:

1. The directional stability of the airplane was approximately doubled by increasing the aspect ratio of the original vertical tail by 40 percent while increasing the vertical-tail area by only 12 percent. The directional stability of the airplane at 300 miles per hour with the original vertical tail corresponded to a value of C_{n_β}, the variation of yawing-moment coefficient with sideslip angle, of 0.00058; whereas with the enlarged vertical tail the estimated value of C_{n_β} was 0.00127. The pilots considered the directional stability of the airplane inadequate with the original vertical tail but satisfactory with the enlarged vertical tail.

2. The addition of a large ventral fin to the airplane with the original vertical tail caused a moderate increase in directional stability for small sideslip angles at low airspeeds but no consistent appreciable change in directional stability at high speeds. The effect of the ventral fin on the directional characteristics of the airplane with the enlarged vertical tail was generally much less than the corresponding effect when used with the original vertical tail.

3. Rudder-force reversals, which occurred in sideslips at low speeds for high engine powers with the original vertical tail, were eliminated by incorporation of the ventral fin. Similar rudder-force reversals which occurred with the enlarged vertical tail were eliminated by addition of the ventral fin, a small dorsal fin, or a combination of the dorsal and ventral fins.

4. A consistent small decrease in directional stability due to increasing altitude occurred in low speed, high-engine-power sideslips, and this effect was attributed to the increased propeller blade angles required to maintain a given indicated airspeed at higher altitudes.

5. The various vertical-tail modifications had a measurable effect on the variation of rudder pedal force with indicated airspeed for fixed rudder tab setting and normal rated power; however, the force variations provided by the various configurations were all desirably small.

6. Greater changes in rudder angle were required to offset a given change in engine power with the enlarged vertical tail than with the original vertical tail, particularly at low speeds; however, the rudder power was entirely adequate to cope with the trim change for any of the configurations tested. A rudder pedal force of approximately 50 pounds was required to offset the directional trim change due to changing the engine power from engine-idling to rated-power conditions; this change of pedal force was largely independent of both airspeed and vertical-tail configuration.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Air Force Base, Va., *November 21, 1946.*

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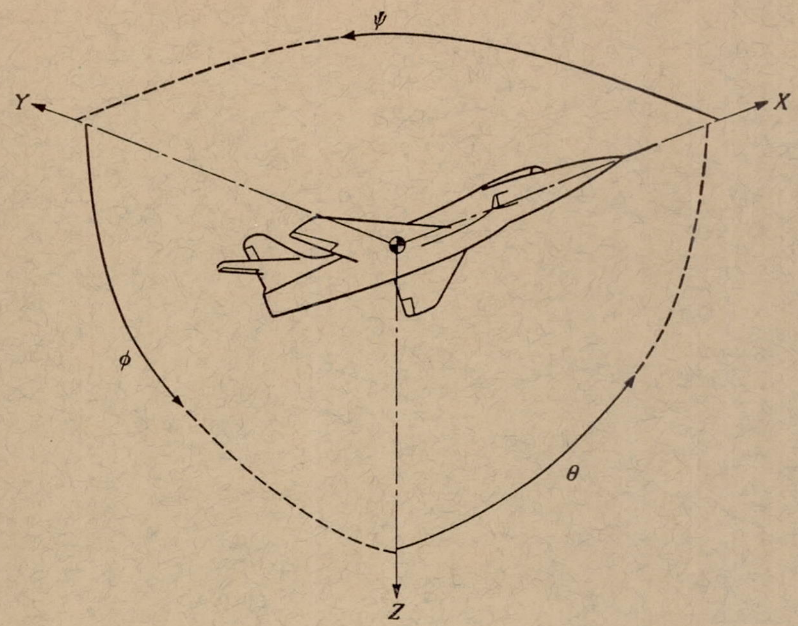
U. S. GOVERNMENT PRINTING OFFICE: 1950



Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter
p Geometric pitch
p/D Pitch ratio
V' Inflow velocity
V_s Slipstream velocity
T Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$
P Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$
C_s Speed-power coefficient$=\sqrt[5]{\frac{\rho V^5}{P n^2}}$
η Efficiency
n Revolutions per second, rps
Φ Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec
1 metric horsepower=0.9863 hp
1 mph=0.4470 mps
1 mps=2.2369 mph
1 lb=0.4536 kg
1 kg=2.2046 lb
1 mi=1,609.35 m=5,280 ft
1 m=3.2808 ft